Docket No. 614.1921/PIK

TITLE OF THE INVENTION

ACOUSTO-OPTICAL TUNABLE FILTERS CASCADED TOGETHER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based on, and claims priority to, Japanese application 10-038908, filed February 20, 1998, in Japan, and which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to acousto-optical tunable filters cascaded together. More specifically, the present invention relates to acousto-optical tunable filters cascaded together and controlled by RF signals generating beats with different phases.

2. Description of the Related Art

Optical communication systems using fiber optical transmission lines are being used to transmit relatively large amounts of information. However, as users require larger amounts of information to be rapidly transmitted, and as more users are connected to the systems, a further increase in the transmission capacity of optical communication systems is required.

Therefore, there is a continual effort in increase transmission capacity of optical communication systems. For example, through improvements in the modulation rate, optical communication systems with modulation rates in the giga-order bits per second (Gb/s) rate are now in practical use. However, optical communication systems having a transmission capacity of tera-order bits per second (Tb/s) may be required for an optical communication system to handle future demands, such as those imposed by the transmission of images.

Improvements in the modulation rate will not, by itself, be enough to handle these future demands.

Therefore, wavelength division multiplexing (WDM) is becoming an indispensable technique for increasing the transmission capacity of optical communication systems. With WDM, a plurality of wavelengths (or "channels"), each carrying information, are multiplexed together and transmitted through a single optical fiber as a WDM signal. This transmitted WDM signal is then received and demultiplexed back into individual wavelengths, so that the information can be obtained from the individual wavelengths. In this manner, a plurality of wavelengths are transmitted through a single optical fiber. This can be contrasted to conventional approaches where a single wavelength is transmitted through a single optical fiber.

Some WDM optical communication systems require wavelength multiplexing such that a few wavelengths to about one-hundred (100) wavelengths are multiplexed together over a wide band. Also, some WDM optical communication systems require wavelength intervals as wide as 1 nm to tens of nm.

Acousto-optical tunable filters (AOTF) are a type of optical wavelength filter that is becoming indispensable in WDM optical communications systems. With an AOTF, wavelength characteristics of the filter can be controlled by changing an RF signal applied to the AOTF, to thereby provide a selectively tunable wavelength filter. AOTFs will be very useful in optical components such as optical add/drop multiplexers (ADM), optical cross-connects, and optical switches.

For example, FIG. 1 is a diagram illustrating an optical ADM node. Referring now to FIG. 1, an optical ADM node 100 receives a light 102 which includes optical wavelength-multiplexed signals of wavelength 1 to wavelength

8. The wavelength-multiplexed light 102 is input to a separator 104 in optical ADM node 100.

Separator 104 separates wavelength 1 to wavelength 4 from wavelength-multiplexed light 102 and permits wavelength 5 to wavelength 8 to pass therethrough.

The lights passing through separator 104 are input to a coupler 106. Coupler 106 couples lights having wavelengths 1' to 4' with the lights of 5 to 8, and outputs a wavelength-multiplexed light 108 via an output node.

An acousto-optical tunable filter (AOTF) can be used as separator 104 or coupler 108 to arbitrarily change the wavelengths to be separated or coupled, and to arbitrarily change the number of wavelengths to be separated or coupled. As a result, it is easy to modify the system configuration by external control.

FIG. 2 is a diagram illustrating a polarization-independent type AOTF, which is one type of AOTF. With this type of AOTF, the main axis of the refractive index of a waveguide is rotated in response to light of the wavelength corresponding to the frequency of a surface acoustic wave (SAW). Hence, a rotation of the polarization of the propagating light makes it possible to extract or modulate a particular wavelength.

Referring now to FIG. 2, optical waveguides 11 and 12 are formed on a LiNbO3 X-cut substrate by diffusing Ti therein. A transducer 15 that generates a SAW corresponding to an RF signal (radio frequency signal that is an electromagnetic wave equal to or lower than 3000 GHz) is formed on optical waveguides 11 and 12.

In order to extract wavelengths 1 to 4, RF signals with four frequencies corresponding to the coupled wavelengths 1 to 4 are applied to transducer 15.

An input light 1 having the wavelengths 1 to 8 is applied to a waveguide type polarization beam splitter (waveguide type PBS) 16, which

separates input light 1 into a TE-mode light and a TM-mode light. The TM-mode light enters optical waveguide 11, and the TE-mode light enters optical waveguide 12.

The polarization of the light of the wavelengths (wavelength 1 to wavelength 4 in the case shown in FIG. 1) corresponding to the SAWs is rotated from the TM-mode light to the TE-mode light in optical waveguide 11, and is rotated from the TE-mode lights to the TM-mode light in optical waveguide 12.

A waveguide type PBS 17 outputs the TM-mode light in optical waveguide 11 to a pass-through light side and outputs the TE-mode light to a branching light side. Further, waveguide type PBS 17 outputs the TE-mode light in optical waveguide 12 to the pass-through light side and outputs the TM-mode light to the branching light side. Hence, a particular wavelength (wavelength 1 to wavelength 4) can be extracted or modulated.

Absorbers 19 and 20 are SAW absorbers that prevent the SAWs from being reflected by an end surface of the substrate.

The AOTF shown in FIG. 2 can also be used as the coupler shown in FIG. 1. In this case, for example, wavelength 1' to wavelength 4' are input as input light 2, while wavelength 5 to wavelength 8 from the separator are input as input light 1.

Then, waveguide type PBS 16 causes the TM-mode light of the wavelength 5 to wavelength 8 to be incident to optical waveguide 11 and causes the TE-mode light thereof to be incident to optical waveguide 12.

When the RF signals corresponding to wavelength 1' to wavelength 4' are input to transducer 15, the polarization of the corresponding lights is changed from the TE-mode light to the TM-mode light in optical waveguide 11, and is changed from the TM-mode light to the TE-mode light in optical waveguide 12.

Waveguide type PBS 17 outputs the TM-mode light in optical waveguide 11 to the pass-through light side and outputs the TE-mode light to the branching light side. Further, waveguide type PBS 17 outputs the TE-mode light in optical waveguide 12 to the pass-through light side and outputs the TM-mode light to the branching light side.

Unfortunately, with the conventional use of an AOTF, the output can undesireably vary with time. For example, in a case where the AOTF is used to extract a plurality of wavelengths (such as wavelength 1 to wavelength 4), if a plurality of frequencies are applied to transducer 15 of the AOTF, the central frequencies of the band-pass/band-rejection characteristics deviate from the target frequencies with time. Hence, the output of the AOTF varies with time although the input light has a constant power.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide an AOTF configuration having stable output characteristics so that the output does not significantly vary with time.

Objects of the present invention are achieved by providing an apparatus which includes a plurality of acousto-optical tunable filters (AOTF) cascaded together. Each AOTF generates a surface acoustic wave in an optical waveguide in accordance with RF signals applied to the AOTF. A phase of a beat generated by the RF signals applied to one of the plurality of AOTFs is different from a phase of a beat generated by the RF signals applied to a different AOTF of the plurality of AOTFs.

Objects of the present invention are further achieved by providing an apparatus including first and second optical filters cascaded together so that the second optical filter filters light output from the first optical filter. The first and second optical filters each have filtering characteristics controlled in

accordance RF signals applied thereto. Moreover, a phase of a beat generated by the RF signals applied to the first optical filter is different than a phase of a beat generated by the RF signals applied to the second optical filter.

In addition, objects of the present invention are achieved by providing an apparatus including first and second optical filters cascaded together so that the second optical filter filters light output from the first optical filter. The first and second optical filters have filtering characteristics controlled in accordance with first and second RF signals, respectively. The first RF signal has a different phase than the second RF signal.

Further, objects of the present invention are achieved by providing an apparatus having at least five optical filters (such as AOTFs) connected together in a specific configuration. More specifically, a first optical filter filters an input light including a plurality of wavelengths to output first and second output lights. The first output light excludes a wavelength of the plurality of wavelengths selected in accordance with an RF signal applied to the first optical filter for controlling filtering characteristics of the first optical filter. The second output light includes the selected wavelength. A second optical filter filters the first output light with filtering characteristics which reject the selected wavelength in accordance with an RF signal applied to the second optical filter for controlling filtering characteristics of the second optical filter. A third optical filter filters the second output light with filtering characteristics which pass the selected wavelength in accordance with an RF signal applied to the third optical filter for controlling filtering characteristics of the third optical filter. A fourth optical filter filters the filtered, first output light from the second optical filter with filtering characteristics which reject the selected wavelength in accordance with an RF signal applied to the fourth optical filter for controlling filtering characteristics of the fourth optical filter. A fifth optical filter filters the filtered, second output light from the third

optical filter with filtering characteristics which pass the selected wavelength in accordance with an RF signal applied to the fifth optical filter for controlling filtering characteristics of the fifth optical filter. A phase controller controls phases of the RF signals applied to the first, second, third, fourth and fifth optical filters with respect to each other.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects and advantages of the invention will become apparent and more readily appreciated from the following description of the preferred embodiments, taken in conjunction with the accompanying drawings of which:

FIG. 1 (prior art) is a diagram illustrating an optical ADM node.

FIG. 2 (prior art) is a diagram illustrating a conventional AOTF.

FIG. 3 is a diagram illustrating a configuration in which wavelengths arranged in order are made to branch into odd-numbered wavelengths and even-numbered wavelengths.

FIG. 4 is a graph illustrating band-pass filter characteristics of a first AOTF 1 shown in FIG. 3 observed at different times.

FIG. 5 is a graph illustrating band-pass filter characteristics of the first AOTF 1 shown in FIG. 3 observed at different times.

FIG. 6 is a graph illustrating band-rejection filter characteristics of the first AOTF 1 shown in FIG. 3 observed at different times.

FIG. 7 is a graph illustrating band-rejection filter characteristics of the first AOTF 1 shown in FIG. 3 observed at different times.

FIG. 8 is a graph illustrating band-pass filter characteristics of the first AOTF 1 shown in FIG. 3 observed at different times.

FIG. 9 is a graph illustrating band-pass filter characteristics of the first AOTF 1 shown in FIG. 3 observed at different times.

FIG. 10 is a graph illustrating band-rejection filter characteristics of the first AOTF 1 shown in FIG. 3 observed at different times.

FIG. 11 is a graph illustrating band-rejection filter characteristics of the first AOTF 1 shown in FIG. 3 observed at different times.

FIG. 12 is a diagram illustrating a time-based characteristic of a beat signal resulting from two RF signals.

FIG. 13 is a diagram illustrating a time-based characteristic of a beat signal resulting from four RF signals.

FIG. 14 is a diagram illustrating a configuration in which a band-pass/band-rejection filter is composed of two stages, according to an embodiment of the present invention.

FIG. 15 is a diagram illustrating relative phases of RF signals applied to cascaded AOTFs, according to an embodiment of the present invention.

FIG. 16 is a diagram illustrating an intensity distribution of the beat of a surface acoustic wave in the configuration shown in FIG. 14, according to an embodiment of the present invention.

FIGS. 17(A) and 17(B) are diagrams illustrating a time-based characteristic of a beat signal resulting from two RF signals in the configuration shown in FIG. 14, according to an embodiment of the present invention.

FIG. 18 is a graph illustrating band-pass filter characteristics of the first AOTF 1 shown in FIG. 14 observed at different times, according to an embodiment of the present invention.

FIG. 19 is a graph illustrating band-pass filter characteristics of the first AOTF 1 shown in FIG. 14 observed at different times, according to an embodiment of the present invention.

FIG. 20 is a graph illustrating band-rejection filter characteristics of the first AOTF 1 shown in FIG. 14 observed at different times, according to an embodiment of the present invention.

embodiment of the present invention.

FIG. 21 is a graph illustrating band-rejection filter characteristics of the first AOTF 1 shown in FIG. 14 observed at different times, according to an embodiment of the present invention.

FIG. 22 is a diagram illustrating the configuration in FIG. 3 accomplished by the configuration in FIG. 14, according to an embodiment of the present invention.

FIG. 23 is a diagram illustrating a four-wavelength band-pass/band-rejection filter using the configuration shown in FIG. 14, according to an embodiment of the present invention.

FIG. 24 is a diagram illustrating the relative phases of phase shifters in FIG. 23, according to an embodiment of the present invention.

FIGS. 25(A) and 25(B) are diagrams illustrating a time-based variation in the beat signal observed when a four-wavelength band-pass/band-rejection filter is formed by the configuration shown in FIG. 23, according to an embodiment of the present invention.

FIG. 26 is a graph illustrating a characteristic of a four-wavelength band-pass filter formed by the configuration shown in FIG. 23, according to an embodiment of the present invention.

FIG. 27 is a graph illustrating the characteristic of the four-wavelength band-pass filter formed by the configuration shown in FIG. 23, according to an embodiment of the present invention.

FIG. 28 is a graph illustrating a characteristic of a four-wavelength band-rejection filter formed by the configuration shown in FIG. 23, according to an embodiment of the present invention.

FIG. 29 is a graph illustrating characteristics of the four-wavelength band-rejection filter formed by the configuration shown in FIG. 23, according to an embodiment of the present invention.

FIG. 30 is a diagram illustrating phase relationships among phase shifters used when an increased number of band-pass/band-rejection wavelengths is used in the configuration shown in FIG. 23, according to an embodiment of the present invention.

FIG. 31 is a diagram illustrating a band-rejection filter having two stages of AOTFs, according to an embodiment of the present invention.

FIG. 32 is a diagram illustrating a band-pass filter having two stages of AOTFs, according to an embodiment of the present invention.

FIG. 33 is a diagram illustrating a band-pass/band-rejection filter having three stages of AOTFs, according to an embodiment of the present invention.

FIG. 34 is a diagram illustrating a relationship between RF signals and phase shifters in the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 35 is a diagram illustrating an intensity distribution of a beat of surface acoustic waves in the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIGS. 36(A), 36(B) and 36(C) are diagrams illustrating a variation in the beat component resulting from RF signals of two wavelengths in the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 37 is a graph illustrating a characteristic of a two-wavelength band-pass filter using the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 38 is a graph illustrating a characteristic of the two-wavelength band-pass filter using the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 39 is a graph illustrating a characteristic of a two-wavelength

band-rejection filter using the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 40 is another diagram of the characteristic of the two-wavelength band-rejection filter using the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 41 is a diagram illustrating a relationship between RF signals and phase shifters of a four-wavelength band-pass/band-rejection filter using the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIGS. 42(A), 42(B) and 42(C) are diagrams illustrating a variation in the beat component resulting from RF signals of four wavelengths in the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 43 is a graph illustrating a characteristic of a four-wavelength band-pass filter using the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 44 is a graph illustrating the characteristic of the four-wavelength band-pass filter using the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 45 is a graph illustrating a characteristic of a four-wavelength band-rejection filter using the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 46 is a graph illustrating a characteristic of the four-wavelength band-rejection filter using the configuration shown in FIG. 33, according to an embodiment of the present invention.

FIG. 47 is a diagram illustrating a relationship between RF signals and phase shifters when an increased number of wavelengths are employed, according to an embodiment of the present invention.

FIG. 48 is a diagram illustrating a band-rejection filter having a three-stage arrangement, according to an embodiment of the present invention.

FIG. 49 is a diagram illustrating a band-pass filter having a three-stage arrangement, according to an embodiment of the present invention.

FIG. 50 is a diagram illustrating the configuration shown in FIG. 14 is formed on a single substrate, according to an embodiment of the present invention.

FIG. 51 is an additional diagram illustrating the configuration shown in FIG. 14 formed on a single substrate, according to an embodiment of the present invention.

FIGS. 52(A), 52(B), 52(C) and 52(D) are diagrams illustrating a reflection waveguide, according to an embodiment of the present invention.

FIG. 53 is a diagram illustrating the configuration shown in FIG. 33 is formed on a single substrate, according to an embodiment of the present invention.

FIG. 54 is a diagram of an AOTF having a SAW containing layer, according to an embodiment of the present invention.

FIG. 55 is a graph illustrating a characteristic of a four-wavelength band-pass filter by using the configuration shown in FIG. 33 to which the AOTF shown in FIG. 54 is applied, according to an embodiment of the present invention.

FIG. 56 is a graph illustrating a characteristic of a four-wavelength band-pass filter by using the configuration shown in FIG. 33 to which the AOTF shown in FIG. 54 is applied, according to an embodiment of the present invention.

FIG. 57 is a graph illustrating a characteristic of a four-wavelength band-rejection filter by using the configuration shown in FIG. 33 to which the AOTF shown in FIG. 54 is applied, according to an embodiment of the

present invention.

FIG. 58 is a graph illustrating a characteristic of a four-wavelength band-rejection filter by using the configuration shown in FIG. 33 to which the AOTF shown in FIG. 54 is applied, according to an embodiment of the present invention.

FIG. 59 is a diagram illustrating an optical communication system employing a band-pass/band-rejection filter according to the above embodiments of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Reference will now be made in detail to the present preferred embodiments of the present invention, examples of which are illustrated in the accompanying drawings, wherein like reference numerals refer to like elements throughout.

FIG. 3 is a diagram illustrating a configuration in which separator 104 shown in FIG. 1 is formed by two stages of AOTFs. Referring now to FIG. 3, odd-numbered wavelengths among the wavelengths arranged in order are selected by a first AOTF 1, while even-numbered wavelengths are selected by a second AOTF 2. An optical input in which wavelength 1 to wavelength 8 are multiplexed is input to first AOTF 1. In first AOTF 1, RF signals of frequencies f1 and f3 corresponding to wavelengths 1 and 3, respectively, are input to a transducer 15-1.

A waveguide type PBS 16-1 receives the light of wavelengths 1 to 8 as input light 1, and separates the input light 1 into TE-mode light and TM-mode light. The TM-mode light enters an optical wavelength path 11-1, and the TE-mode light enters an optical wavelength path 12-1.

The polarization of optical wavelengths 1 and 3 corresponding to SAWs of f1 and f3 is rotated from the TM-mode light to the TE-mode light in optical

wavelength path 11-1, and is rotated from the TE-mode light to the TM-mode light in optical wavelength path 12-1.

In a wavelength type PBS 17-1, the TM-mode light in the optical wavelength path 11-1 is output to an output-1 side, and the TE-mode light existing therein is output to an output-2 side. Further, in wavelength path type PBS 17-1, the TE-mode light in optical wavelength path 12-1 is output to the output-1 side, and the TM-mode light existing therein is output to the output-2 side. Hence, wavelengths 1 and 3 are output from the output-2 side, and wavelengths 2 and 4 to 8 are output from the output-1 side.

The output 1 of first AOTF 1 is input to an optical amplifier 22 which performs a level adjustment by amplifying the light attenuated by first AOTF 1. The output of the optical amplifier is input to second AOTF 2 as input light 1.

In second AOTF 2, RF signals of frequencies f2 and f4 corresponding to wavelengths 2 and 4, respectively, are input to a transducer 15-2. A waveguide type PBS 16-2 receives the light of wavelengths 2 and 4 to 8, and separates the input light into TE-mode light and TM-mode light. The TM-mode light enters an optical waveguide 11-2, and the TE-mode light enters an optical waveguide 12-2.

The polarization of optical wavelengths 2 and 4 corresponding to SAWs of f2 and f4 is rotated from the TM-mode light to the TE-mode light in optical waveguide 11-1, and is rotated from the TE-mode light to the TM-mode light in optical waveguide 12. Hence, wavelengths 2 and 4 are output from the output-2 side, and the wavelengths 4 to 8 are output from output-1 side.

Reference numbers 13-1 and 13-2 of first AOTF 1 and second AOTF 2 indicate layers, which contain the SAWs within optical waveguides 11-1, 11-2, 12-1 and 12-2 and which are formed on the optical waveguides on the surface of the substrate.

With the above configuration, the odd-numbered wavelengths among the wavelengths arranged in order are selected by first AOTF 1 and the even-numbered wavelengths are selected by second AOTF 2, so that individual wavelengths around the particular wavelengths can be extracted even when the AOTFs have a wide pass-through wavelength range and a wide branching wavelength range.

FIGS. 4 through 7 are graphs illustrating wavelength characteristics of the band-pass/band-rejection performance of first AOTF 1. More specifically, FIGS. 4 through 7 shows results of a simulation that is conducted so that wavelength characteristics are simulated at constant intervals in a state in which frequencies f1 and f3 are applied to transducer 15-1 by setting wavelengths 1 and 3 subjected to the band-pass or band-rejection operation to 1.5484 μm and 1.5500 μm, respectively.

FIGS. 4 and 5 show the band-pass characteristics viewed from the output-2 side of first AOTF 1. It can be seen from the figures that the central frequencies of the filter with respect to the required wavelengths 1.5484 μm and 1.5500 μm observed at different times vary with time and that the 1.5484 μm and 1.5500 μm required to pass through the filter are attenuated with time. The above results in a level variation in the output signal. Particularly, the simulation result of FIG. 5 shows that the band-pass wavelength characteristic periodically changes with time.

FIG. 6 shows the band-rejection characteristic viewed from the output-1 side of first AOTF 1. Originally, an attenuation equal to or greater than -50 dB is expected at the wavelengths 1.5484 μm and 1.5500 μm, while the actual attenuation is reduced to approximately –25 dB.

FIG. 7 shows a characteristic obtained by extending the characteristic of FIG. 6 on the time basis. It can be seen from FIG. 7 that the wavelengths that are attenuated around the wavelengths 1.5484 μm and 1.5500 μm vary

periodically with time. This phenomenon holds true for a case where an increased number of band-pass or band-rejection wavelengths are set in the AOTF.

FIGS. 8 through 11 are graphs illustrating characteristics obtained when RF signals of frequencies f1, f2, f3 and f4 are applied to the first AOTF 1, which extracts wavelengths 1 to 4.

FIGS. 8 and 9 show band-pass characteristics viewed from the output-2 side. The following can be seen from FIG. 8 in which first AOTF 1 allows wavelengths 1.5468 μm, 1.5484 μm, 1.5500 μm and 1.5516 μm to pass therethrough. The pass-through level changes with time and the band-pass wavelengths shift to positions other than the peaks of the filter characteristic. Thus, the optical signals having the wanted wavelengths are attenuated.

FIG. 9 shows a characteristic obtained by extending the characteristic of FIG. 8 on the time basis. The wavelengths allowed to pass through first AOTF 1 change periodically with time around the wavelengths 1.5468 μm, 1.5484 μm, 1.5500 μm and 1.5516 μm.

FIG. 10 shows a band-rejection wavelength characteristic viewed from the output-1 side. Originally, an attenuation equal to or greater than -50 dB is expected at the wavelengths 1.5468 μm, 1.5484 μm, 1.5500 μm and 1.5516 μm, while the actual attenuation is reduced to approximately -25 dB.

FIG. 11 shows a characteristic obtained by extending the characteristic of FIG. 10 on the time basis. It can be seen from FIG. 11 that the wavelengths attenuated change periodically around the wavelengths 1.5468 μm, 1.5484 μm, 1.5500 μm and 1.5516 μm.

It can be seen from the above that the band-pass/band-rejection wavelength characteristics can periodically be changed when a plurality of RF signals are applied to the AOTF in order to select a plurality of desired wavelengths.

FIG. 12 is a diagram illustrating a result of a simulation conducted so that the intensity of a beat component of the SAWs obtained by applying two RF signals to first AOTF 1 in order to select two wavelengths is simulated at constant intervals. Thus, FIG. 12 shows a simulation for the first stage of the AOTF configuration.

FIG. 13 is a diagram illustrating a result of a simulation conducted so that the intensity of the beat component of the SAWs observed when four wavelengths are selected by first AOTF 1 is simulated at constant intervals. Thus, FIG. 13 shows a simulation for the first stage of the AOTF configuration.

It can be seen from FIGS. 12 and 13 that the intensity of the beat component shifts with a constant period.

FIG. 14 is a diagram illustrating a configuration of AOTFs directed to solving the problem that the peak of the intensity of the beat component shifts, according to an embodiment of the present invention. The configuration has two stages of AOTFs, and the phases of the beat components caused by the RF signals applied commonly to the AOTFs have a 90° offset between the first and second stages.

Referring now to FIG. 14, an optical input having multiplexed wavelengths 1 to 8 is input to AOTF 1 of the first stage. RF signals of frequencies f1 and f3 corresponding, respectively, to wavelengths 1 and 3 are applied to transducer 15-1 of first AOTF 1. The frequencies f1 and f3 of the RF signals used here are, for example, 176.795 MHz and 176.613 MHz, respectively.

Waveguide type PBS 16-1 receives the light of wavelengths 1 to 8 as input light 1, and separates the input light 1 into TE-mode light and TM-mode light. The TM-mode light enters optical wavelength path 11-1, and the TE-mode light enters optical wavelength path 12-1. The polarization of optical

wavelengths 1 and 3 corresponding to SAWs of f1 and f3 is rotated from the TM-mode light to the TE-mode light in optical waveguide 11-1, and is rotated from the TE-mode light to the TM-mode light in optical waveguide 12-2.

In waveguide type PBS 17-1, the TM-mode light in optical waveguide 11-1 is output to the output-1 side, and the TE-mode light existing therein is output to the output-2 side. Further, in waveguide type PBS 17-1, the TE-mode light in optical waveguide 12-1 is output to the output 1 side, and the TM-mode light is output to output-2 side. Hence, wavelengths 1 and 3 are output from the output-2 side, and wavelengths 2 and 4 to 8 are output from output-1 side.

Waveguide type PBS 16-2 separates the received light into the TE-mode light and the TM-mode light. The TM-mode light enters optical waveguide 11-2, and the TE-mode light enters optical waveguide 12-2. At that time, the RF signal of the frequency f3 is processed by a phase shifter 122-2, which shifts the phase of the RF signal by 180 degrees with respect to the original phase thereof input to first AOTF 1. Coupler 14-2 couples the 180°-phase shifted RF signal of the frequency f3 with the RF signal of the frequency f1.

The RF signals of the frequency f1 and the 180°-phase shifted RF signal of the frequency f3 are applied to transducer 15-2 via coupler 14-2. Hence, the lights of wavelengths 1 and 3 which cannot be deleted perfectly due to time-based variations in the central frequencies of the band-rejection of first AOTF 1 have polarization which is rotated from the TM-mode light to the TE-mode light in optical waveguide 11-2 and which is rotated from the TE-mode light to the TM-mode light in optical waveguide 12-2. In waveguide type PBS 17-2, the TM-mode light and the TE-mode light in optical waveguide 11-2 are respectively output to the output-1 side and the output-2 side, and the TE-mode light and the TM-mode light in optical waveguide 12-2 are

respectively output to the output-1 side and the output-2 side.

Hence, by changing the phase of the RF signal applied to second AOTF 2 by phase shifter 122-2, it is possible to shift the phase of the peak of the beat component of the RF signal and to delete, from the output of second AOTF 2, the wavelength components of wavelengths 1 and 3 which are not deleted totally at particular times by first AOTF 1. Thus, time-based variations in the amount of attenuation of the band-rejection components can be suppressed.

The output 2 of first AOTF 1 is input to input 1 of a third AOTF 3. A waveguide type PBS 16-3 separates the light into the TE-mode light and the TM-mode light, which are input to optical waveguides 12-3 and 11-3, respectively. At that time, a transducer 15-3 is supplied with the output of coupler 14-2, which is the same as the RF signal applied to second AOTF 2.

The polarization of the lights having wavelengths 1 and 3 from first AOTF 1 is changed from the TM-mode light to the TE-mode light in optical waveguide 11-3, and is changed from the TE-mode light to the TM-mode light in optical waveguide 12-3. Then, the above lights enter a waveguide type PBS 17-3.

Waveguide type PBS 17-3 outputs the TM-mode light and the TE-mode light in optical waveguide 11-3 to the output-1 side and the output-2 side, respectively, and outputs the TE-mode light and the TM-mode light in optical waveguide 12-3 to the output-1 side and the output-2 side, respectively.

Hence, even if slightly attenuated lights of wavelengths 1 and 3 with the pass-through peaks offset in first AOTF 1 and the lights of wavelengths 1 and 3 that are not attenuated at all are output at different times, the timing at which the attenuation is applied can be controlled by third AOTF 3. Hence, it is possible to provide lights of wavelengths 1 and 3 that always have an approximately identical amount of transparency.

FIG. 15 is a diagram illustrating the relative phases of RF signals applied to first AOTF 1, second AOTF 2 and third AOTF 3, according to an embodiment of the present invention.

FIG. 16 is a diagram illustrating an intensity distribution of the phases of the RF signals applied to first AOTF 1, second AOTF 2 and third AOTF 3, according to an embodiment of the present invention. More specifically, FIG. 16 indicates the case of a two-stage AOTF configuration when two channels are selected. Referring now to FIG. 16, S1 indicates a beat intensity distribution of the surface acoustic wave propagated from the electrode of first AOTF 1 to an absorber 20-1. S2 and S3 indicate beat intensity distributions of the surface acoustic waves respectively propagated from the electrodes of second AOTF 2 and third AOTF 3 to absorber 20-1. In FIG. 16, the phase difference between beats is 90°.

FIGS. 17(A) and 17(B) are diagrams illustrating time-based variations in the intensities of the beat components of the RF signals applied to first AOTF 1 of the first stage shown in FIG. 14 and second AOTF 2 and third AOTF 3 of the second stage, according to an embodiment of the present invention.

More specifically, FIG. 17(A) shows a variation in the intensity of the beat component resulting from the RF signals applied to first AOTF 1 as a function of time. Thus, FIG. 17(A) shows the variation for the first stage of the AOTF configuration. FIG. 17(B) shows variations in the intensities of the beat components of the RF signals applied to second AOTF 2 and third AOTF 3 as a function of time. Thus, FIG. 17(B) shows the variation for the second stage of the AOTF configuration.

FIGS. 18 and 19 are graphs illustrating band-pass characteristics obtained by integrating the characteristics of first AOTF 1 and third AOTF 3 shown in FIG. 14 obtained at different times, according to an embodiment of

the present invention. Variations in the central frequencies shown in FIGS. 18 and 19 are less than those shown in FIGS. 4 and 5.

FIGS. 20 and 21 are graphs illustrating band-rejection characteristics obtained by integrating the characteristics of first AOTF 1 and second AOTF 2 shown in FIG. 14 obtained at different times, according to an embodiment of the present invention. Variations in the central frequencies shown in FIGS. 20 and 21 are less than those shown in FIGS. 6 and 7.

FIG. 22 is a diagram illustrating an AOTF configuration which accomplishes the configuration shown in FIG. 3 by using the configuration shown in FIG. 14 which can suppress wavelength variations of the filters, according to an embodiment of the present invention. Referring now to FIG. 22, the connections from first AOTF 1 to third AOTF 3 that form the odd-numbered wavelength selecting part for selecting the odd-numbered wavelengths and the RF signals are the same as those in the configuration shown in FIG. 14.

The connections from a fourth AOTF 4 to a sixth AOTF 6 that form the even-numbered wavelength selecting part for selecting the even-numbered wavelengths are the same as shown in FIG. 14. The RF signals are directed to selecting wavelengths 2 and 4. The RF signal of the frequency f4 used for selecting wavelength 4 among the RF signals applied to the fifth and sixth AOTFs is offset by 180 degrees by a phase shifter 122-4 with respect to the original phase thereof.

With the above configuration, it is possible to individually extract any of the wavelengths while suppressing variations in the pass-through or branching wavelengths.

FIG. 23 is a diagram illustrating an AOTF configuration in which four wavelengths are selected by using the configuration shown in FIG. 14, according to an embodiment of the present invention. Referring now to FIG.

23, the RF signals of the frequencies f1 (176.978 MHz), f2 (176.795 MHz), f3 (176.613 MHz) and f4 (176.431 MHz) respectively corresponding to wavelengths 1.5468 μm, 1.5484 μm, 1.5500 μm and 1.5516 μm to be selected are applied to couplers 14-1 and 14-2 via switches SW1, SW2, SW3 and SW4 and phase shifters P11, P12, P13, P14, P21, P22, P23 and P24.

The output of coupler 14-1 is input to first AOTF 1 via a power control part 60. The output of coupler 14-2 is input to second AOTF 2 and third AOTF 3.

FIG. 24 is a diagram illustrating an example of the relative phases of the phase shifters in FIG. 23, according to an embodiment of the present invention. More specifically, as indicated in FIG. 24, phase shifters P23 and P21 are set so as to have an offset of 180 degrees with respect to the original phases of the RF signals having the frequencies f2 and f4. The other phase shifters are set so that the received signals are applied to the couplers without any phase offset.

FIGS. 25(A) and 25(B) are graphs illustrating time-based variations in the peak intensities of the RF signals obtained under the phase condition shown in FIG. 24, according to an embodiment of the present invention. More specifically, FIG. 25(A) shows a variation in the peak intensity of the beat component caused by the RF signals applied to first AOTF 1 as a function of time. Thus, FIG. 25(A) shows the variation for the first stage of the AOTF configuration. FIG. 25(B) shows a variation in the peak intensities of the beat components of the RF signals applied to second AOTF 2 and third AOTF 3 as a function of time. Thus, FIG. 25(B) shows the variation for the second stage of the AOTF configuration.

FIG. 26 is a graph illustrating a band-pass characteristic obtained by integrating the characteristics of first AOTF 1 and third AOTF 3 shown in FIG. 23 obtained at different times, according to an embodiment of the present

invention.

FIG. 27 is a graph illustrating a characteristic obtained by extending the characteristic of FIG. 26 on the time basis, according to an embodiment of the present invention. Variations in the central frequencies of the band-pass filter shown in FIGS. 26 and 27 are less than those shown in FIGS. 8 and 9.

FIG. 28 is a graph illustrating a band-rejection characteristic obtained by integrating the characteristics of first AOTF 1 and second AOTF 2 shown in FIG. 23 obtained at different times, according to an embodiment of the present invention.

FIG. 29 is a graph illustrating a characteristic obtained by extending the characteristic of FIG. 28 on the time basis, according to an embodiment of the present invention. Variations in the central frequencies of the band-rejection filter shown in FIGS. 28 and 29 are less than those shown in FIGS. 10 and 11.

FIG. 30 is a diagram illustrating an example of phase conditions for a case where wavelengths to be subjected to the band-pass/band-rejection operation are added to the configuration shown in FIG. 23, according to an embodiment of the present invention. The RF signals of the frequencies f5 and f6 are added, and, as indicated by FIG. 30, the phase of the RF signal of the frequency f6 applied to each of second AOTF 2 and third AOTF 3 is offset by 180 degrees with respect to the original phase thereof. It can be seen that it is enough to offset half of the RF signals applied to second AOTF 2 and third AOTF 3 by 180 degrees in order to shift the phases of the beat components of the RF signals applied to the AOTFs.

FIG. 31 is a diagram illustrating the AOTF configuration shown in FIG. 23, which functions as a band-rejection filter, according to an embodiment of the present invention.

FIG. 32 is a diagram illustrating a variation of the AOTF configuration shown in FIG. 23, which functions as a band-pass filter, according to an

embodiment of the present invention.

FIG. 33 is a diagram illustrating a variation of the configuration shown in FIG. 23, according to an embodiment of the present invention. Referring now to FIG. 33, a fourth AOTF 4 and a fifth AOTF 5 of a third stage follow second AOTF 2 and third AOTF 3 of the second stage in order to suppress time-based variations in the central frequencies in the band-pass/band-rejection operations.

FIG. 34 is a diagram illustrating an example of phase conditions of the configuration in FIG. 33, according to an embodiment of the present invention. More specifically, FIG. 34 shows phase conditions of phase shifters that are employed when switches SW1 and SW2 in the configuration shown in FIG. 33 are turned ON, and the RF signals of the frequencies f1 and f2 are applied to the first to fifth AOTFs. Phase shifter P22 that supplies the RF signals to second AOTF 2 and third AOTF 3 is set to provide an offset of 120 degrees to the phase of the frequency f2. Phase shifter P33 that supplies the RF signals to fourth AOTF 4 and fifth AOTF 5 is set to provide an offset of 240 degrees with respect to the phase of the frequency f2.

FIG. 35 is a diagram illustrating a peak intensity distribution of the surface acoustic waves from the electrode to the SAW absorber under the phase condition shown in FIG. 34, according to an embodiment of the present invention. Thus, FIG. 35 illustrates the case for a three-stage AOTF configuration. Referring now to FIG. 35, S1 indicates an intensity distribution of the beat component of the surface acoustic waves in first AOTF 1. S2 and S4 respectively indicate intensity distributions of the beat components of the surface acoustic waves in second AOTF 2 and third AOTF 3. S3 and S5 respectively indicate intensity distributions of the beat components of the surface acoustic waves in fourth AOTF 4 and fifth AOTF 5. FIG. 35 illustrates a case when two channels are selected. The phase difference

between beats is 60°.

FIGS. 36(A), 36(B) and 36(C) are diagrams illustrating the phases of the peaks of the beat components of the RF signals in the respective AOTFs shown in FIG. 33 with the RF signals of f1 and f2 applied thereto, according to an embodiment of the present invention.

More specifically, FIG. 36(A) shows the phase of the peak of the beat component resulting from the RF signals in first AOTF 1 of the first stage. FIG. 36(B) shows the phases of the peaks of the beat components of the RF signals in second AOTF 2 and third AOTF 3 of the second stage. FIG. 36(C) shows the phases of the peaks of the beat components of the RF signals in fourth AOTF 4 and fifth AOTF 5 of the third stage.

FIG. 37 is a graph illustrating a band-pass characteristic obtained by integrating the characteristics of first AOTF 1 and third AOTF 3 shown in FIG. 33 with the RF signals of f1 and f2, and obtained at different times, according to an embodiment of the present invention.

FIG. 38 is a graph illustrating a characteristic obtained by extending the wavelength characteristic shown in FIG. 37 on a time basis, according to an embodiment of the present invention. The time-based variations in the characteristics of the band-pass filter shown in FIGS. 37 and 38 are the smallest among those shown FIGS. 4, 5, 18 and 19.

FIG. 39 is a graph illustrating a band-rejection characteristic obtained by integrating the characteristics of the second AOTF 2 and the fourth AOTF 4 shown in FIG. 33 with the RF signals of f1 and f2, and obtained at different times, according to an embodiment of the present invention.

FIG. 40 is a graph illustrating a characteristic obtained by extending the wavelength characteristic shown in FIG. 39 on a time basis, according to an embodiment of the present invention. The time-based variations in the characteristics of the band-rejection filter shown in FIGS. 39 and 40 are the

smallest among those shown FIGS. 6, 7, 20 and 21.

FIG. 41 is a diagram illustrating phase conditions of beat components of the RF signals in the respective stages obtained when the switches SW1 through SW4 in the configuration shown in FIG. 33 are turned ON, and four wavelengths are subjected to the band-pass or band-rejection operation, according to an embodiment of the present invention. As indicated in FIG. 41, the phase shifter P22 that supplies the RF signals to second AOTF 2 and third AOTF 3 is set to provide an offset of 120 degrees to the phase of the frequency f2. The phase shifter P23 is set to provide an offset of 240 degrees with respect to the phase of the frequency f3. The phase shifter P33 that supplies the RF signals to fourth AOTF 4 and fifth AOTF 5 is set to provide and offset of 240 degrees with respect to the phase of the frequency f2. The phase shifter P32 is set to provide an offset of 120 degrees with respect to the phase of the frequency f2.

FIGS. 42(A), 42(B) and 42(C) are graphs illustrating time-based peak variations in the beat components of the RF signals applied to the respective AOTFs under the above phase conditions, according to an embodiment of the present invention.

More specifically, FIG. 42(A) shows the phase of the peak of the beat component of the RF signals in the first AOTF 1 of the first stage. FIG. 42(B) shows the phases of the peaks of the beat components of the RF signals in the second AOTF 2 and the third AOTF 3 of the second stage. FIG. 42(C) shows the phases of the peaks of the beat components of the RF signals in the fourth AOTF 4 and the fifth AOTF 5 of the third stage.

FIG. 43 is a graph illustrating a wavelength characteristic obtained by integrating the time-based band-pass filter characteristics of the first, third and fifth AOTFs in the configuration shown in FIG. 33 with the phase conditions of FIG. 42, according to an embodiment of the present invention.

FIG. 44 is a graph illustrating a characteristic obtained by extending the wavelength characteristic of FIG. 43 on the time basis, according to an embodiment of the present invention.

It can be seen that time-based variations in the characteristics of the band-pass filter shown in FIGS. 43 and 44 are less than those shown in FIGS. 8, 9, 26 and 27.

FIG. 45 is a graph illustrating a wavelength characteristic obtained by integrating the time-based band-rejection filter characteristics of the first, second and fourth AOTFs in the configuration shown in FIG. 33 with the phase conditions of FIG. 41, according to an embodiment of the present invention.

FIG. 46 is a diagram illustrating a characteristic obtained by extending the wavelength characteristic of FIG. 45 on a time basis, according to an embodiment of the present invention.

It can be seen that time-based variations in the characteristics of the band-pass filter shown in FIGS. 45 and 46 are less than those shown in FIGS. 10, 11, 28 and 29.

FIG. 47 is a diagram illustrating an example of phase relationships among RF signals respectively applied to AOTFs in a case where an increased number of wavelengths are to be selected in the configuration shown in FIG. 33, according to an embodiment of the present invention. As indicated in FIG. 47, the phases of the RF signals applied to second AOTF 2 and third AOTF 3 are increased by 120 degrees each time the number of wavelengths is increased by one, while the phases of the RF signals applied to fourth AOTF 4 and fifth AOTF 5 are decreased by 120 degrees each time the number of wavelengths is decreased by one. Thus, the peaks of the beat components of the RF signals can be shifted between the AOTFs, as shown in FIG. 42. Thus, it is possible to reduce time-based variations around the central

frequencies in the band-pass/band-rejection characteristics.

FIG. 48 is a diagram illustrating a variation of the configuration shown in FIG. 33, operating as a band-rejection filter, according to an embodiment of the present invention.

FIG. 49 is a diagram illustrating another variation of the configuration shown in FIG. 33, operating as a band-pass filter, according to an embodiment of the present invention.

FIG. 50 is a diagram illustrating the configuration shown in FIG. 33 formed on a single substrate, such as, for example, a LiNbO3 substrate, according to an embodiment of the present invention.

FIG. 51 is a diagram illustrating a variation of the configuration shown in FIG. 50, directed to down sizing of the device by providing a mirror to an end surface of the substrate in order to return the lights, according to an embodiment of the present invention. Referring now to FIG. 51, a reflection device includes optical waveguide reflectors 18-1 and 18-2 and is provided to prevent lights from being returned to first AOTF 1.

FIGS. 52(A), 52(B), 52(C) and 52(D) are diagrams illustrating a configuration of a waveguide type reflector and a configuration of the ordinary waveguide type PBS, according to an embodiment of the present invention.

More specifically, FIG. 52(A) shows the configuration of the waveguide type PBS. When the length of a crossing path where the optical waveguides cross at an opening angle $\Theta 1$ is changed, a polarization characteristic as shown in FIG. 52(B) is obtained. Hence, in order to form the PBS, the length of the crossing path may be set to a length Lc1 in which the maximum splitting ratio of the TE mode and minimum splitting ratio of the TM mode are available.

The above concept as applied to a waveguide reflector shown in FIG. 52(C). When the length of a crossing path where the optical waveguides cross

at an opening angle Θ2 is changed, a polarization characteristic as shown in FIG. 52(D) is obtained. Hence, in order to guide the light to only the waveguide P2, the length of the crossing path may be set to a length Lc2 in which the both the modes are coupled to the identical waveguide P2. It is thus possible to prevent the reflected light from returning to the waveguide to which the above light enters by cutting the waveguide at the position equal to half the length Lc2 and providing a reflecting device such as a reflection film to the end surface of the waveguide obtained by cutting.

When the opening angles Θ1 and Θ2 are approximately 0.8°, the length Lc1 is approximately 400 μm and the length Lc2 is approximately 1100 μm. As the opening angles Θ1 and Θ2 become greater, the lengths Lc1 and Lc2 tend to become longer.

FIG. 53 is a diagram illustrating a configuration directed to realizing the configuration shown in FIG. 33 by using the waveguide type reflector shown, for example, in FIG. 52(C) and 52(D), according to an embodiment of the present invention.

FIG. 54 is a diagram of an AOTF having a SAW containing layer, according to an embodiment of the present invention.

FIGS. 55 through 58 are graphs illustrating characteristics obtained by a modification of the configuration shown in FIG. 33 in which an AOTF is used such that a layer for containing the SAW is obliquely provided with respect to the waveguides, as shown in FIG. 54, according to an embodiment of the present invention.

As compared to the characteristics shown in FIGS. 43 through 46, it can be seen that side lobes are not substantially observed in the characteristics shown in FIGS. 55 through 58.

It is possible to reduce side lobes by applying the AOTF shown in FIG. 54 to the first through fifth AOTFs used in FIGS. 14, 23, 31, 32, 48, 49, 50,

51 and 53.

As described above, by cascading AOTFs and shifting the phases of the beat components caused by the RF signals commonly applied to the AOTFs, the positions in which the light is most greatly attenuated are different, in the respective AOTFs, from each other on the time basis. Hence, it is possible to reduce variations in the central frequencies in the band-pass/band-rejection operations in the AOTFs. If the power of the input light is constant, it is possible to reduce variations in the power of light caused in the band-pass/band-rejection operations of the AOTFs.

FIG. 59 is a diagram illustrating a WDM optical communication system employing a band-pass/band-rejection filter according to the above embodiments of the present invention. Referring now to FIG. 59, a plurality of individual transmitters (TX) 100 transmit optical signals at different wavelengths. The optical signals are then multiplexed together by a multiplexer (MUX) 102 into a WDM signal which is transmitted through an optical fiber transmission line 104. Thus, individual transmitters 100 and multiplexer 102 together form a transmitter 106 transmitting a WDM signal through transmission line 104. A demultiplexer (DEMUX) 108 demultiplexes the WDM signal into individual optical signals received by respective receivers (RX) 110. Thus, demultiplexer 108 and receivers 110 together from a receiver 112 receiving the transmitted WDM signal through transmission line 104. Typically, optical amplifiers, such as optical amplifier 114, would be positioned along transmission line 104.

An optical filtering apparatus 116 filters the WDM signal as the WDM signal travels through transmission line 104. Optical filtering apparatus 116 can have any of the cascaded optical filter arrangements shown herein. For example, optical filtering apparatus 116 can have a configuration as illustrated, for example, in FIGS. 14 or 33. Thus, optical filtering apparatus 116 can be

used, for example, as part of an ADM node which adds/drops wavelengths from the WDM signal propagating through transmission line 104.

In FIG. 59, optical filtering apparatus 116 is positioned between transmitter 106 and receiver 112. However, optical filtering apparatus 116 is not intended to be limited to this positioned, and can be located in various other positions depending on the intended use of optical filtering apparatus 116.

Moreover, FIG. 59 illustrates examples of transmitters and receivers. However, the present invention is not intended to be limited to these examples. Instead, there are many different configurations of transmitters and receivers.

According to the above embodiments of the present invention, a plurality of AOTFs are cascaded, each generating a surface acoustic wave in an optical waveguide by applying an RF signal to an electrode provided on a substrate and selectively outputting a light having a wavelength corresponding to the RF signal. Each of the plurality of AOTFs is supplied with respective RF signals. A phase of a beat generated by the RF signals applied to one of the AOTFs is different from that of a beat generated by the RF signals applied to another one of the AOTFs. As indicated above, according to various embodiments of the present invention, a phase difference between RF signals applied to the AOTFs is equal to a value obtained by dividing 360° by the number of stages of the AOTFs. Thus, the difference in phase of the beats generated by the RF signals applied to first and second cascaded AOTFs in first and second stages, respectively, is equal to a value obtained by dividing 180° by the number of stages of cascaded AOTFs. Therefore, in accordance with the above embodiments of the present invention, the phase difference depends on the number of stages of AOTFs, not on the number of wavelengths, or channels, in a WDM signal.

According to the above embodiments of the present invention, all of the

AOTFs cascaded together can be formed on a single substrate. Typically, such a substrate would be, for example, a LiNbO3 substrate. However, the present invention is not intended to be limited to this substrate material, and other substrate materials can be used in accordance with semiconductor design principles.

Moreover, according to the above embodiments of the present invention, if the AOTFs are formed on a substrate, a reflection device can be provided on an end surface of the substrate, for reflecting the lights resulting from the band-pass and band-rejection operations of the first AOTF so that reflected lights can be applied to subsequent AOTFs, such as to second and third AOTFs. A distance from the reflection device to an output waveguide of the first AOTF and another distance from a position in which the second and third AOTFs are coupled to the reflection device can be set equal to a distance in which reflected lights are not coupled with the first AOTF.

According to various of the above embodiments of the present invention, the AOTFs weight surface acoustic waves applied to waveguides.

According to the present invention, AOTFs are connected in a multiple-stage formation and the phases of the beat components generated by the RF signals applied commonly to the AOTFs are different. Hence, the AOTFs are caused to have different times when the light is most greatly attenuated. It is thus possible to reduce variations in the central frequencies in the band-pass/band-rejection operation of the AOTFs. When the input light has a constant power, variations in the power of the light after the band-pass/band-rejection operation can be reduced.

Generally, the present invention is applicable to optical filters having filtering characteristics which are controlled by RF signals applied thereto. For example, the present invention is applicable to mode conversion type AOTFs which convert TM to TE, and convert TE to TM. Thus, the present

invention is also applicable to fiber type AOTFs.

The above-embodiments of the present invention relate to the "beat" generated by an RF signal applied to an optical filter. Generally, a "beat" refers to a variation in the intensity of a composite wave which is formed from two distinct waves with different frequencies. Generally, for example, in an AOTF, the beat is a variation in the envelope of the amplitude versus position characteristics of a surface acoustic wave (SAW). The concept of "beat" in an optical filter, such as an AOTF, is well-known.

Various of the above embodiments of the present invention describe specific RF frequencies for RF signals applied to an optical filter, and describe specific frequencies of selected wavelengths. However, the present invention in not intended to be limited to any specific frequencies for the RF signals, or to any specific frequencies for the selected wavelengths.

Further, various of the above embodiments of the present invention describe specific examples of phase shift amounts for RF signals applied to different stages of an AOTF configuration. However, the present is not intended to be limited to these examples of phase shift amounts.

Although a few preferred embodiments of the present invention have been shown and described, it would be appreciated by those skilled in the art that changes may be made in these embodiments without departing form the principles and spirit of the invention, the scope of which is defined in the claims and their equivalents.